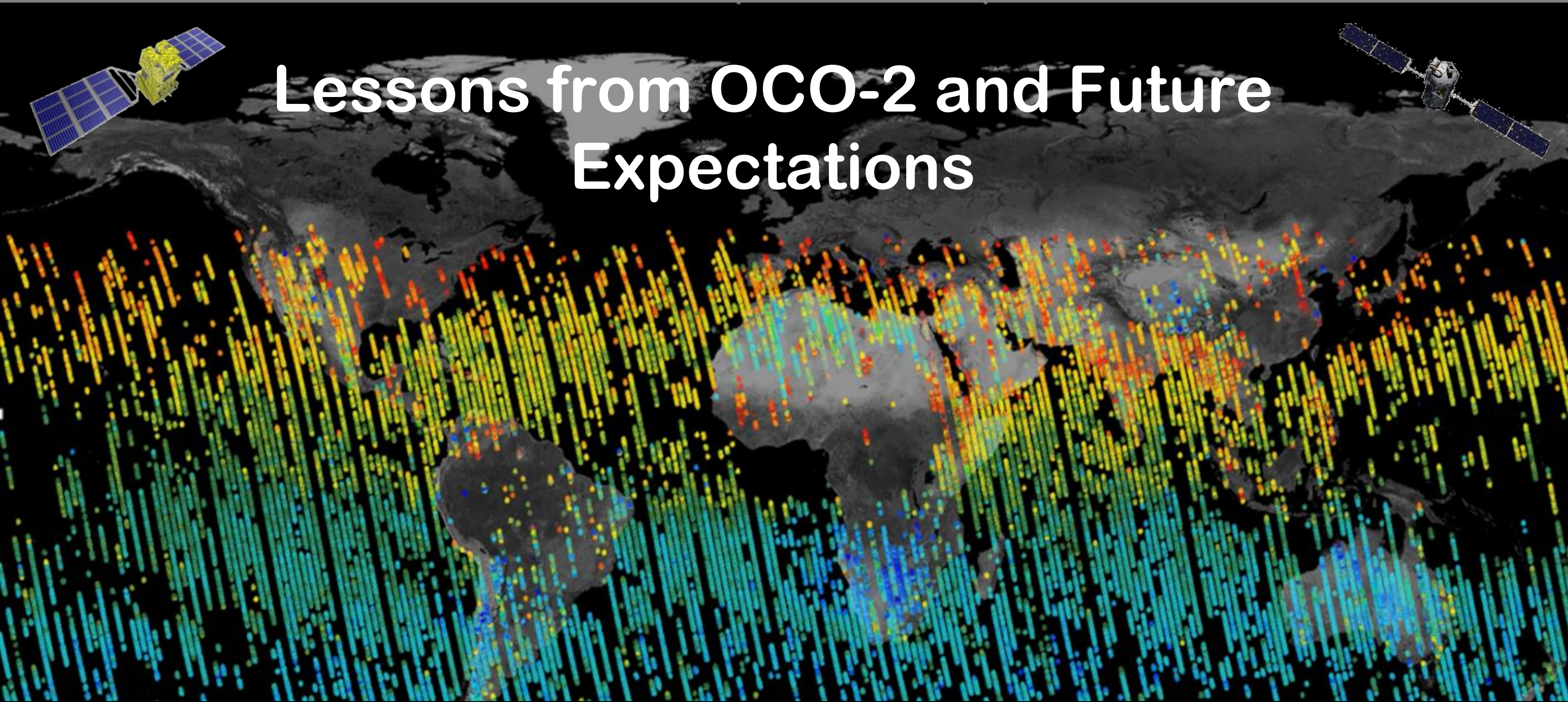
The International Workshop on Next Generation CO_2 Monitoring Satellite

Lessons from OCO-2 and Future Expectations



Hartmut Boesch for

David Crisp, Jet Propulsion Laboratory, California Institute of Technology

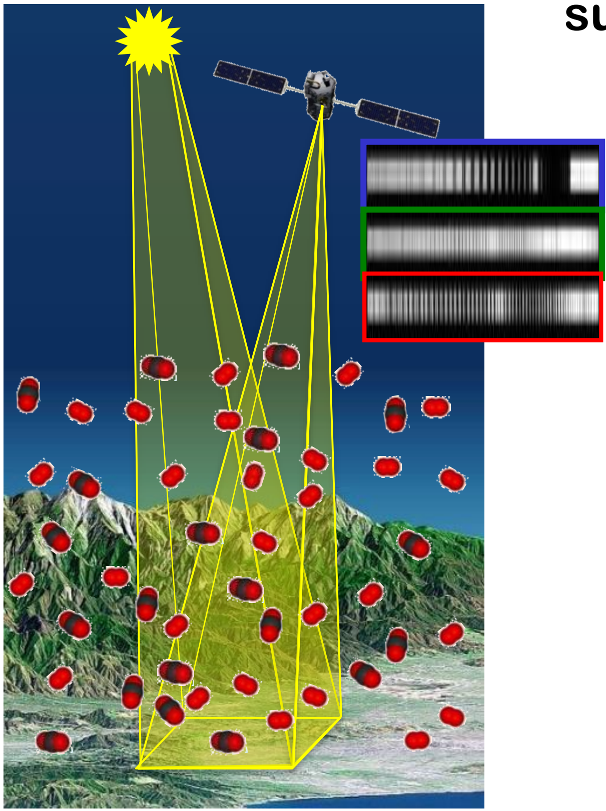
1-3 November 2017

Lessons Learned from OCO-2

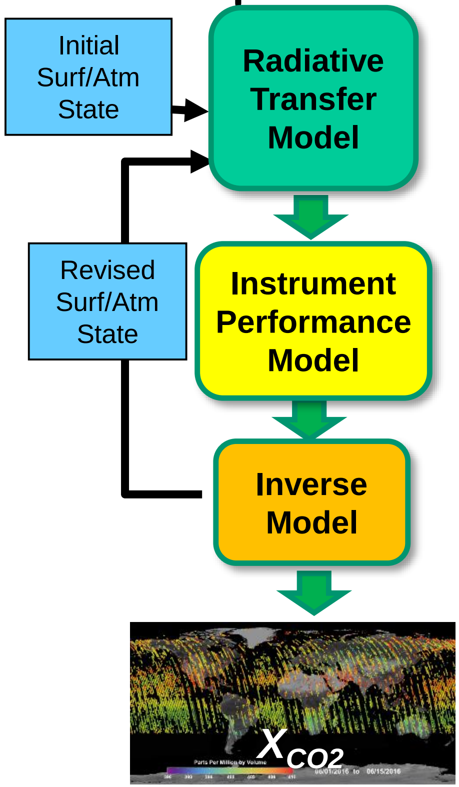
- High accuracy and low bias are both essential
- High spatial resolution (footprint area < 4 km^2) critical for
  - Quantifying emissions from compact sources
    - X_{CO2} anomaly associated with a given CO_2 injection is inversely proportional to the area of the footprint
  - Gathering full-column data in presence of patchy clouds
- Coverage: Imaging rather than sampling the CO_2 field
  - Critical for tracking emission plumes and resolving anthropogenic emission sources from the natural background
- Proxies (SIF, CO, and NO_2) may be needed for attribution
- Improved remote sensing retrieval algorithms and carbon flux inversion models are critical for exploiting the information from space based greenhouse gas measurments

Measuring CO_2 from Space

- **Record** spectra of CO_2 and O_2 absorption in reflected sunlight



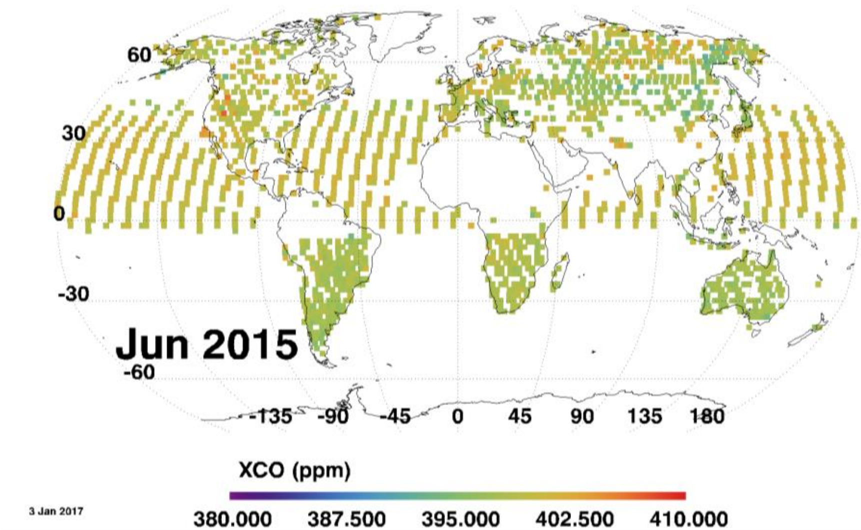
Retrieve variations in the column averaged CO_2 dry air mole fraction, X_{CO2} over the sunlit hemisphere



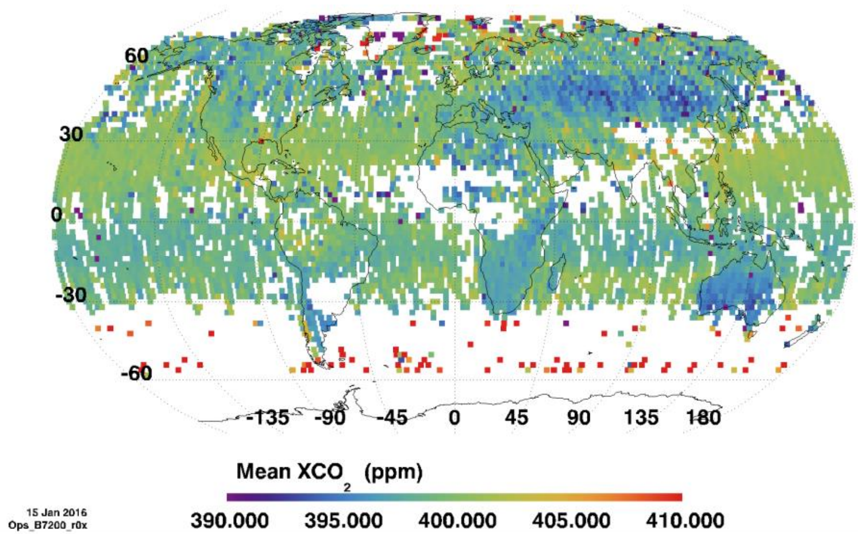
Validate measurements to ensure X_{CO2} accuracy of 1 ppm (0.25%)

Retrieving X_{CO2} from GOSAT and OCO-2 Data

GOSAT



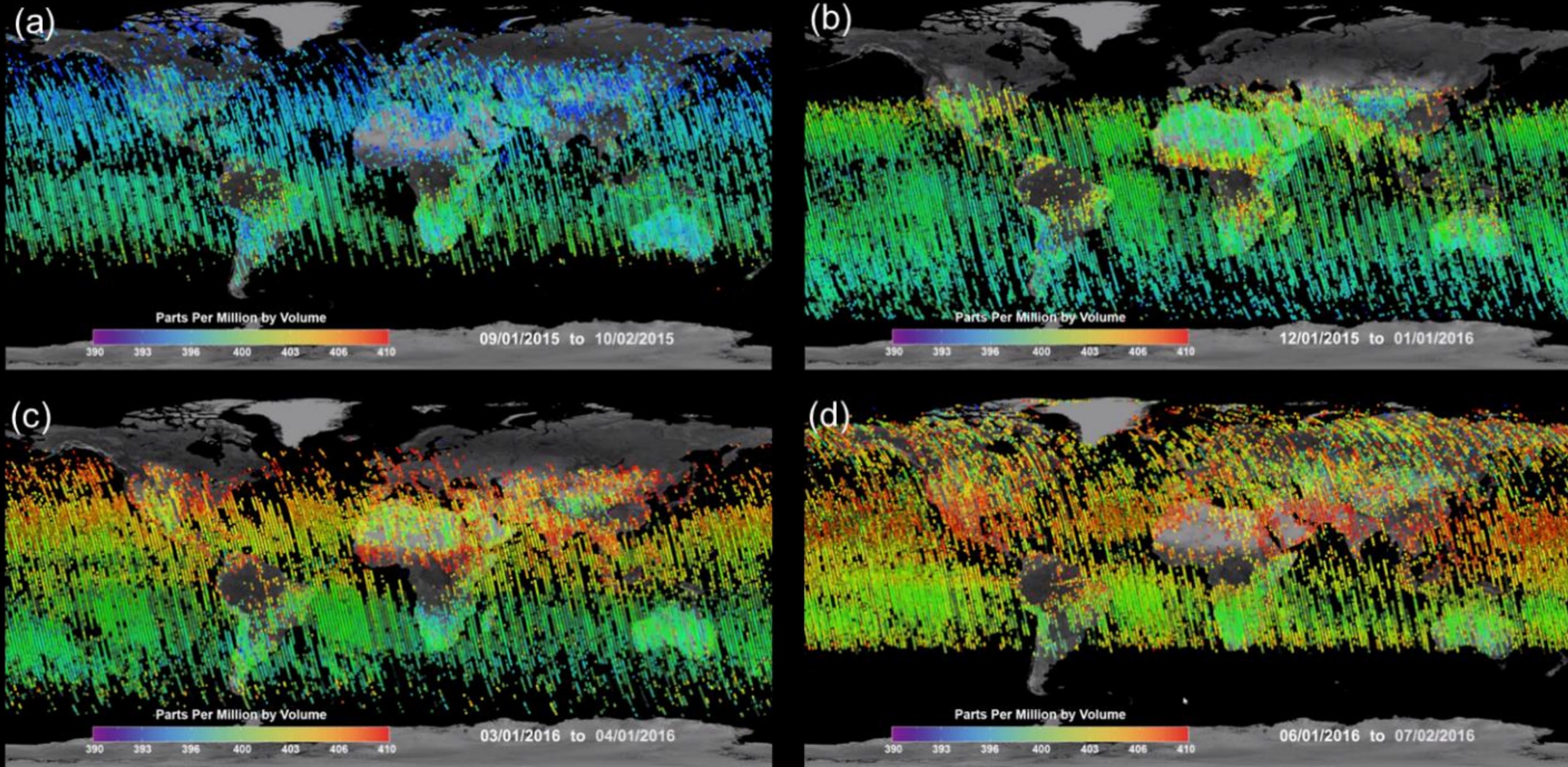
OCO-2



GOSAT TANSO-FTS has been returning 300-100 cloud free soundings/day since Apr 2009. The ACOS/GOSAT team has been using these data to retrieve X_{CO2}.

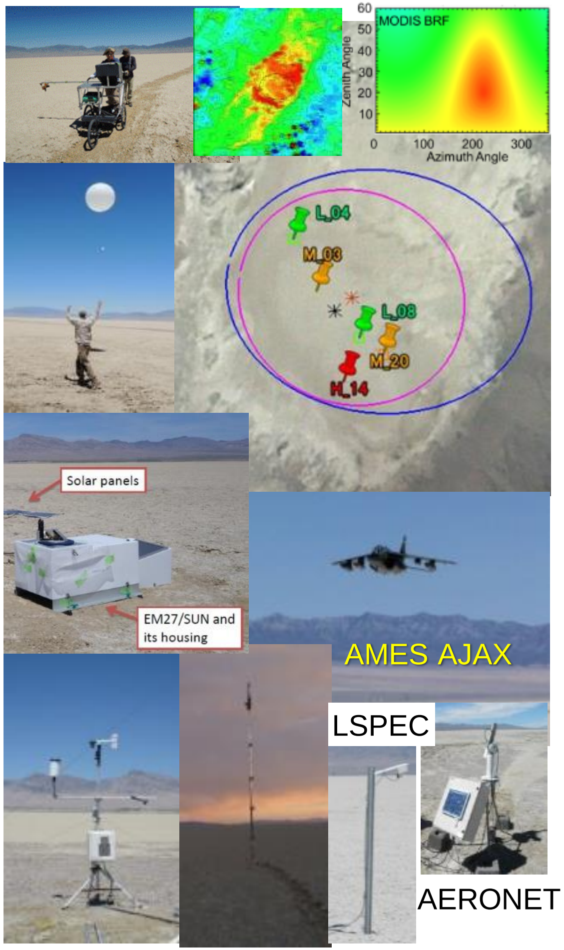
OCO-2 has been returning 25000 to 70000 soundings/day since Sept 2014. The ACOS/GOSAT algorithm was modified to retrieve X_{CO2} from these data.

OCO-2 Coverage (B7 Product)



Cross-Calibration and Cross-Validation Essential to Combine Data Products

Vicarious Calibration



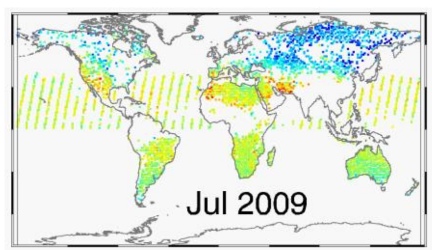
Retrieval Algorithm

Forward Radiative Transfer Model
Spectra + Jacobians

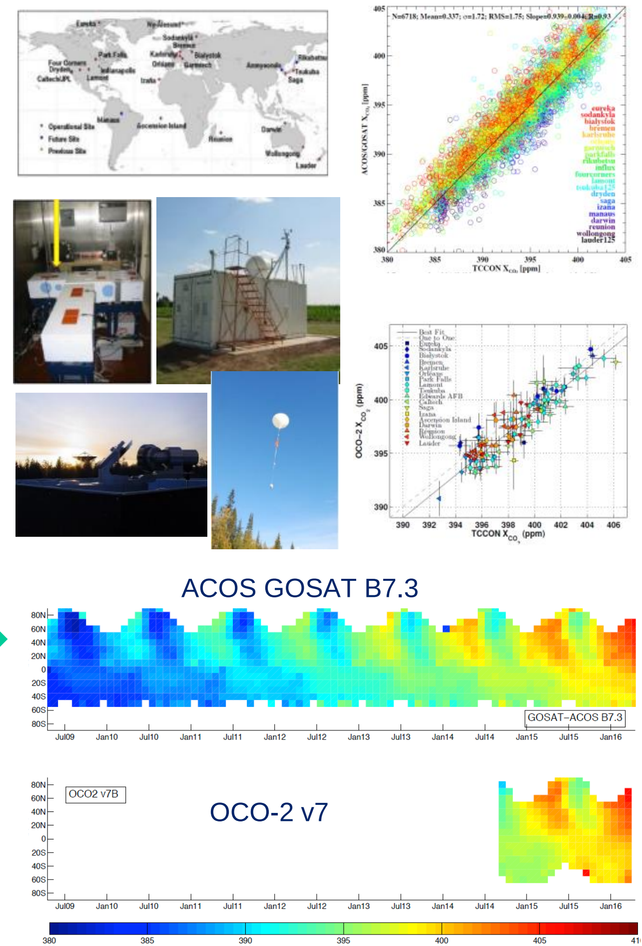
Instrument Model
Spectral+Polarization

Inverse Model
- Compare obs. & simulated spectra
- Update State Vector

?
not converged
converged

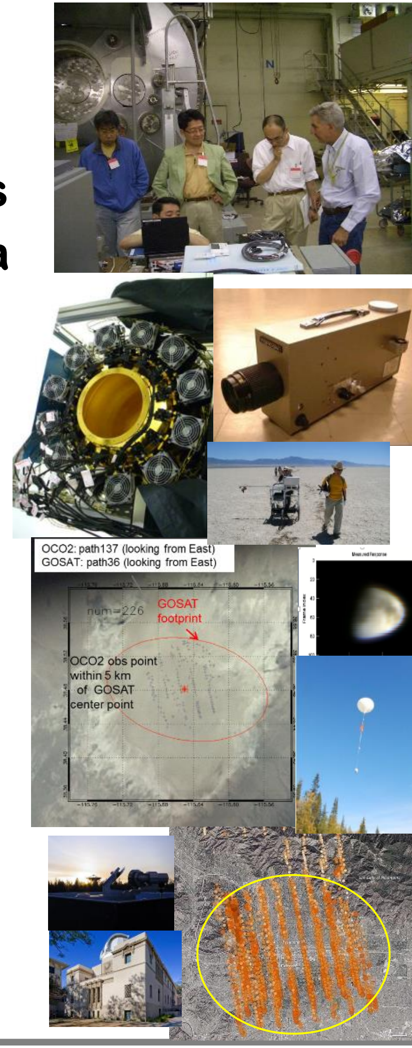


Cross Validation

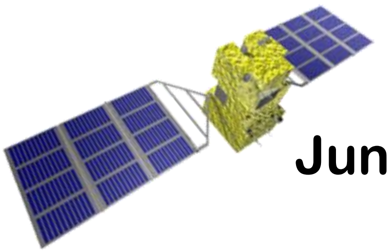


Creating a Combined Data Product: Cross-Calibration and Cross Validation

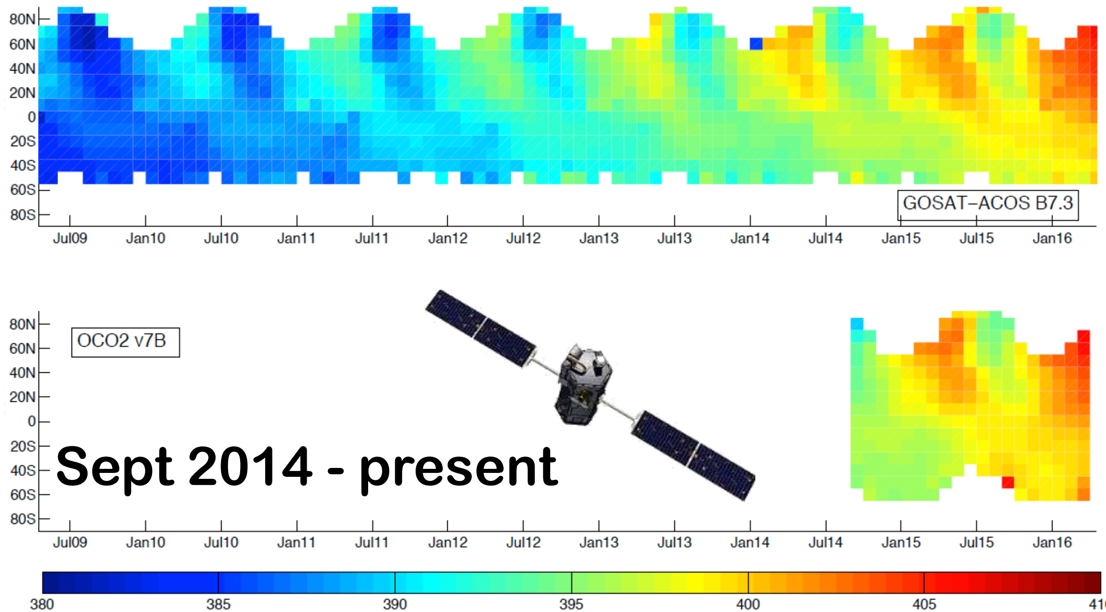
- Pre Launch:
  - Exchange information on best practice for pre-launch instrument characterization
  - Cross calibration of pre-launch radiometric standards
  - Exchange of gas absorption coefficient and solar data
  - Retrieval algorithm development/intercomparison
  - Validation system development (TCCON, aircraft)
  - Multi-Satellite OSSE's – what do you gain with truly coordinated observations
- Post Launch:
  - Cross calibration of solar/lunar/Earth(vicarious: RRV+?) observations
  - Including exchange of solar and lunar standards
  - Cross validation: TCCON, EM27/Sun, and aircraft validation campaigns
  - Continued retrieval algorithm development/intercomparisons



ACOS/GOSAT B7.3, and OCO-2 v7 XCO2



June 2009 - present

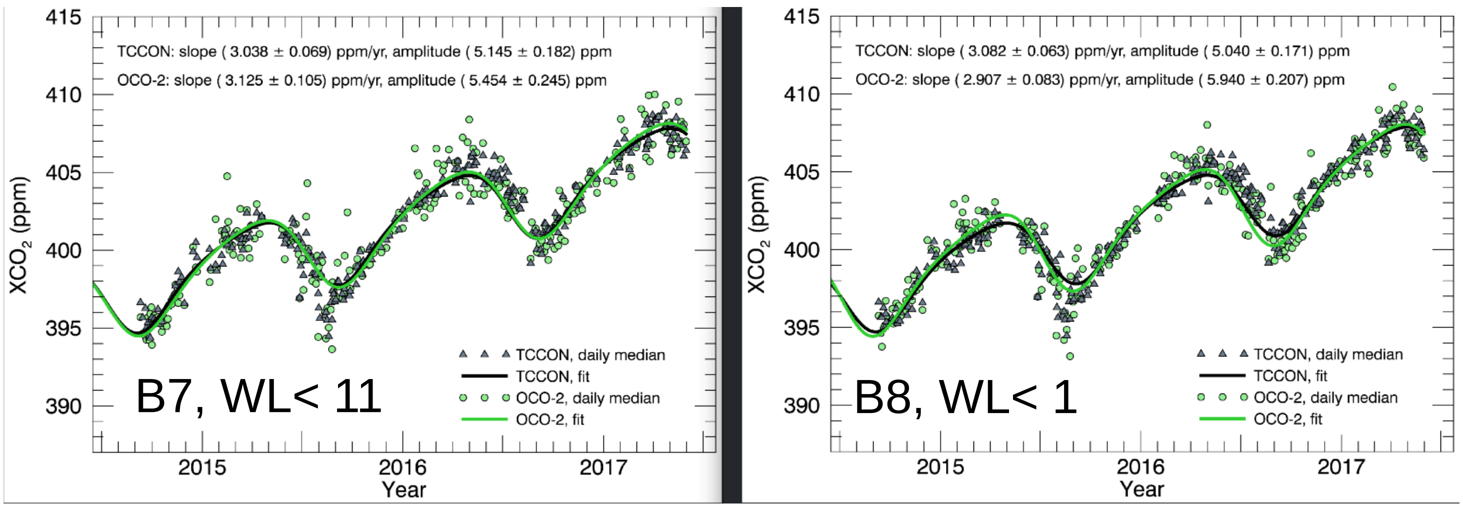


TCCON and other standards have been used to cross validate OCO-2 and GOSAT X_{CO2} to extend the climate data record

- The magnitude of differences between GOSAT-ACOS B7.3 and OCO2 v7r are within ±1 ppm for overlap regions

Validating Space-based Measurements against International Standards

- **GOSAT and OCO-2 data were validated against the Total Column Carbon Observing Network (TCCON)**
- **TCCON is validated against the WMO standards profiles from in situ instruments on aircraft**
- **Other standards, including aircraft campaigns (HIPPO, ACT-America, Atom) also used**
- **These validation methods must be maintained and expanded to support future observations from LEO, GEO and HEO platforms**

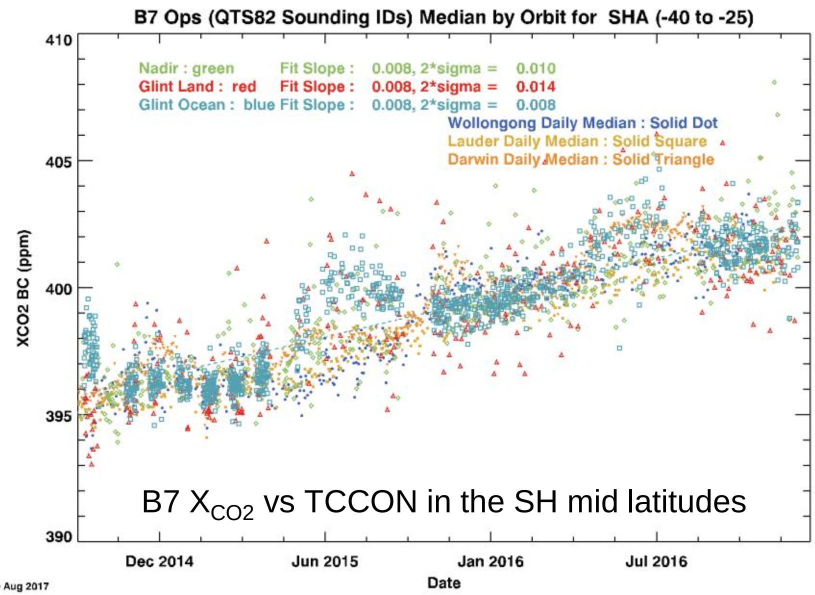


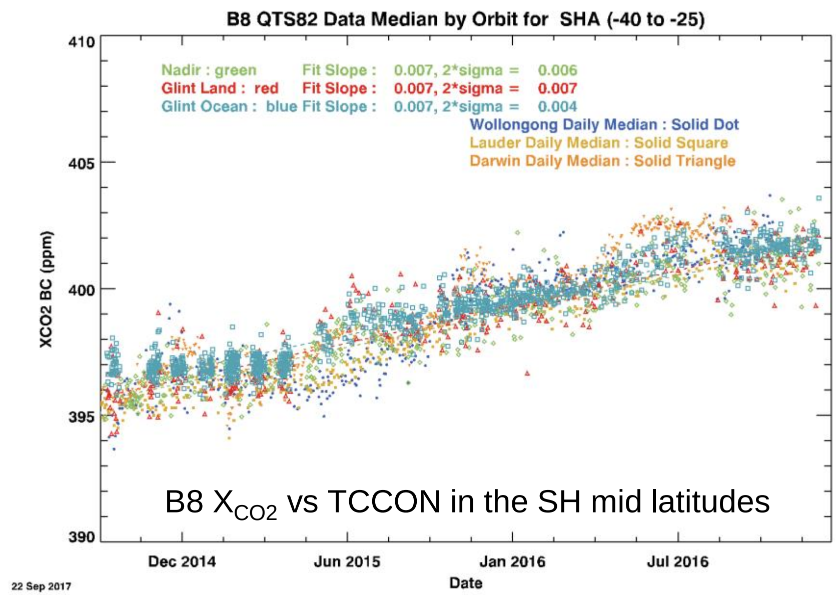
Time series of of OCO-2 B7 (left) and B8 (right) X_{CO2} with the Lamont TCCON X_{CO2}

Lindqvist et al.

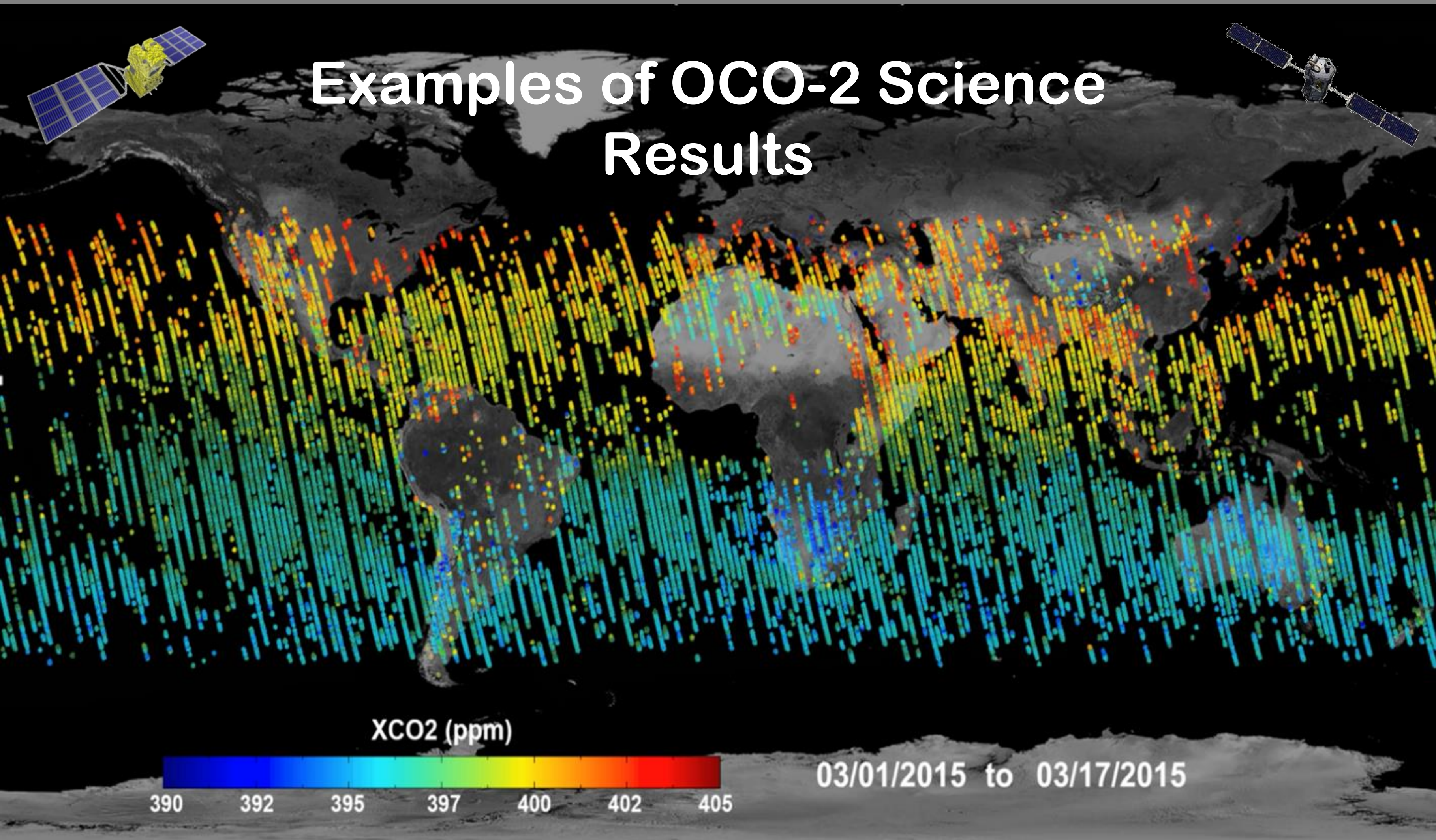
Improved Remote Sensing Retrieval Algorithms are Needed

- **Recent updates in the OCO-2 X_{CO2} retrieval algorithm have reduced both bias and scatter in the X_{CO2} product**
  - **Version 8 (B8) updates include improved radiometric calibration, improved O_2 cross sections, the addition of a stratospheric aerosol layer, a more realistic, non-Lambertian BRDF, updated cloud screening, and other smaller changes**

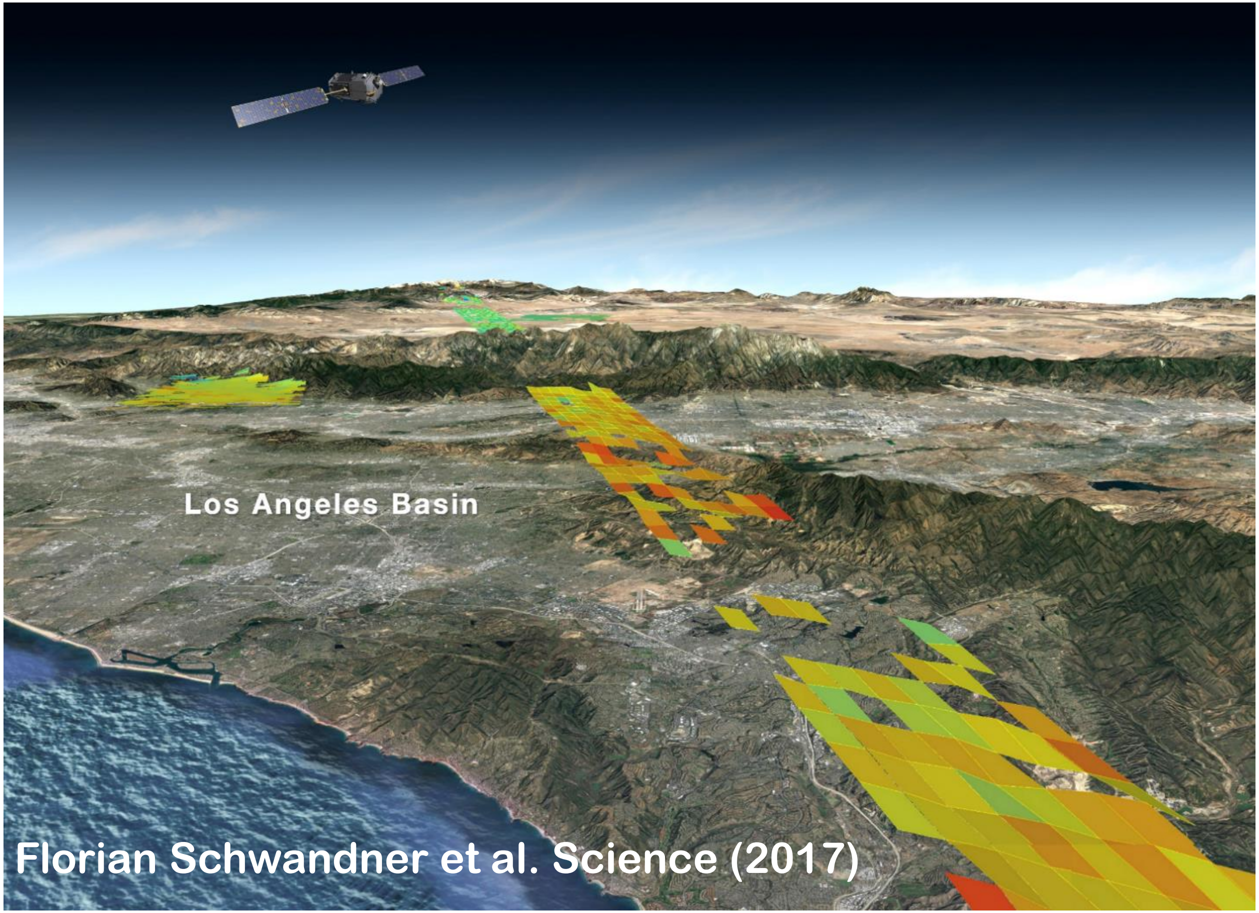


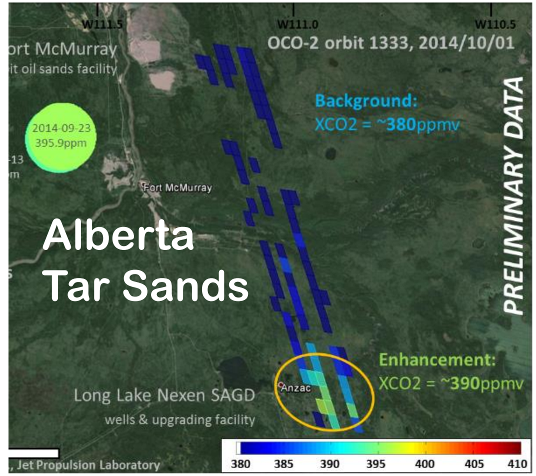


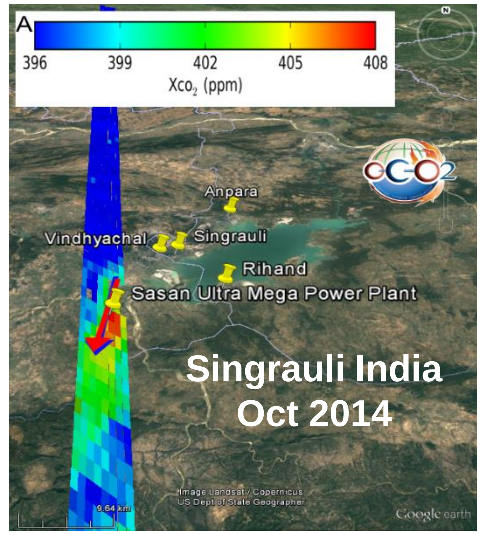
Examples of OCO-2 Science Results



Quantifying Localized Sources



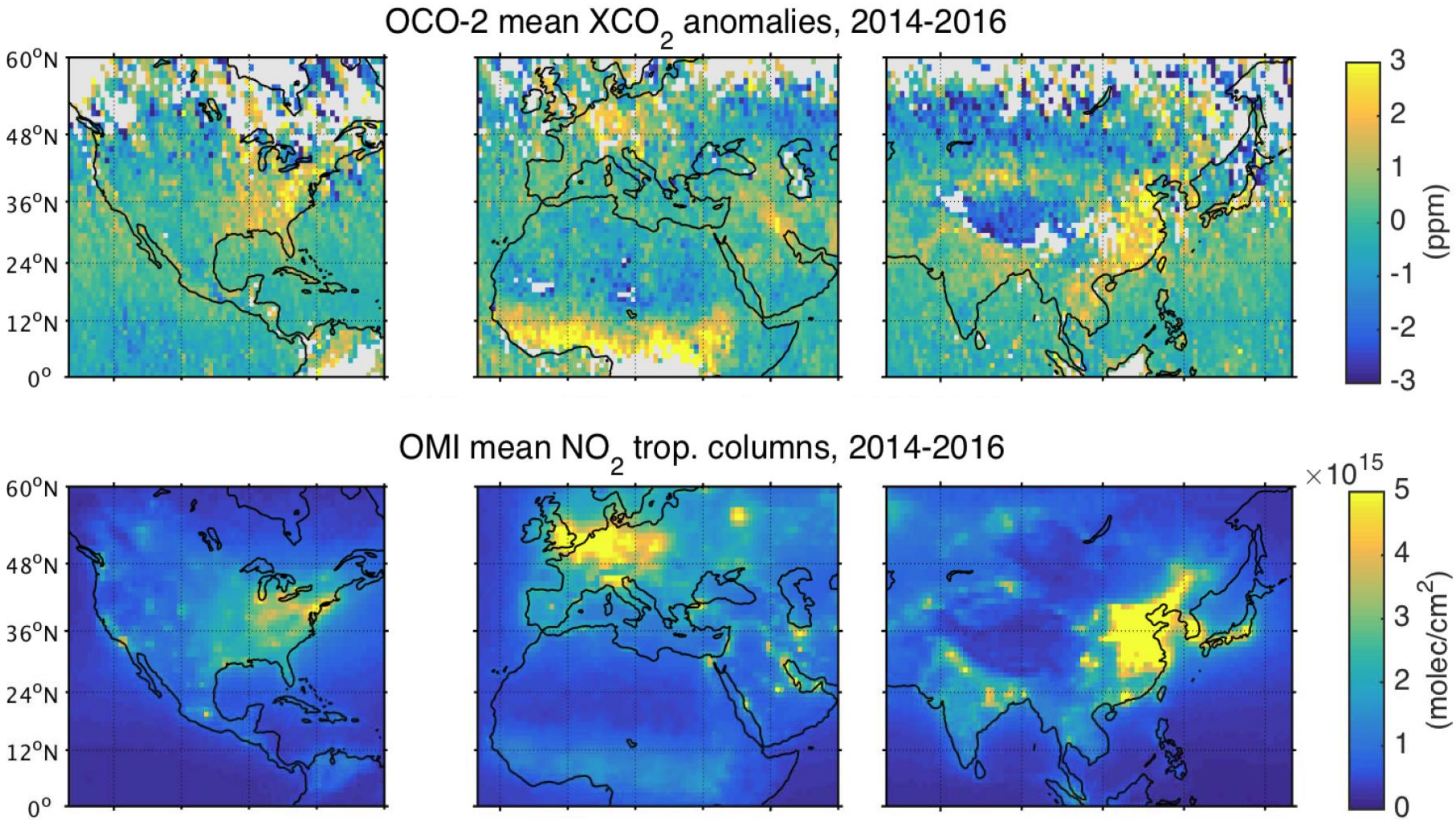




Nassar et al. (GRL 2017)

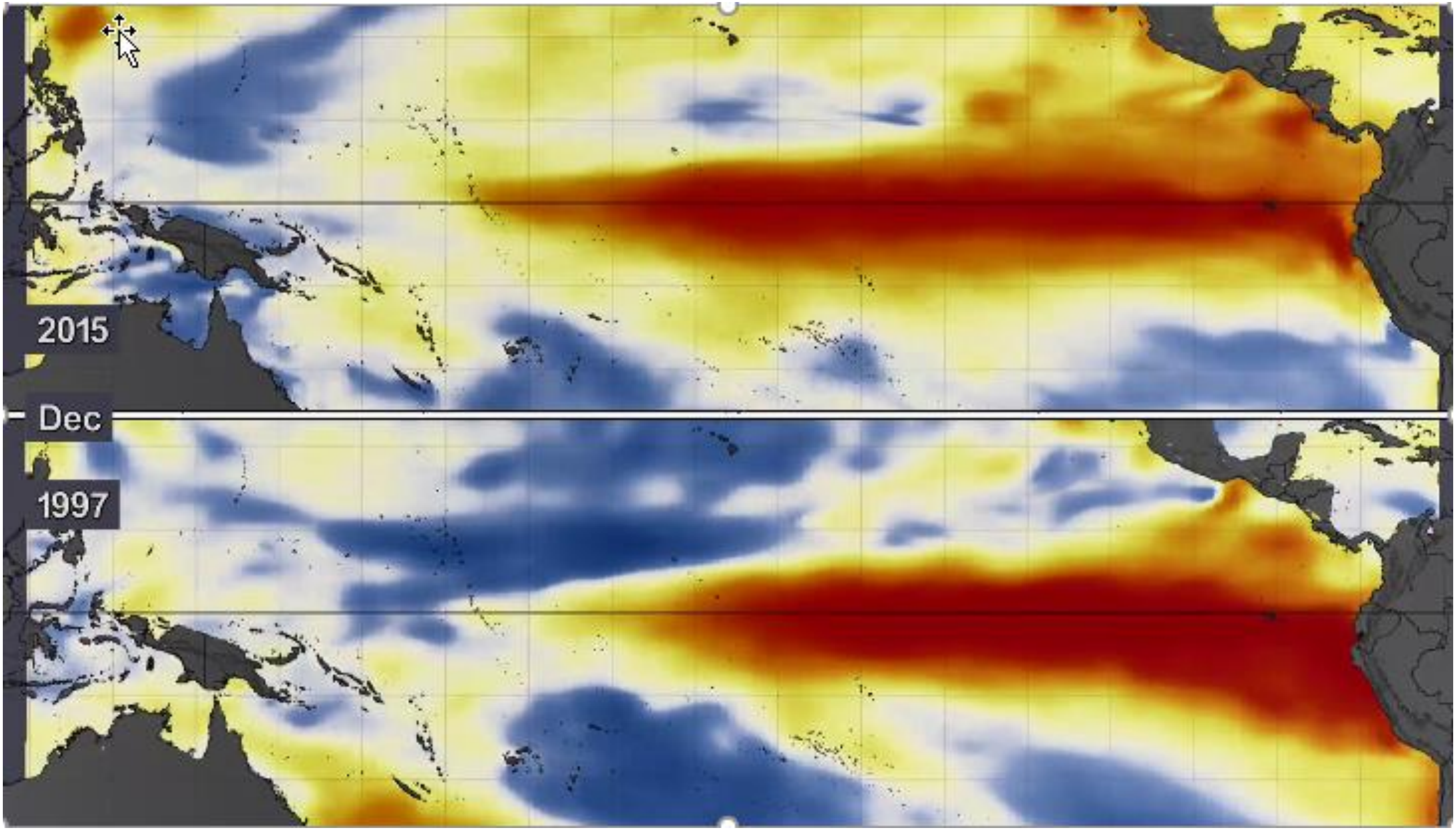
High spatial resolution and full coverage are critical for quantifying localized sources

Proxies, including NO_2 and CO are critical for Attributing Sources of CO_2 Emissions



Janne Hakkarainen et al. GRL (2016)

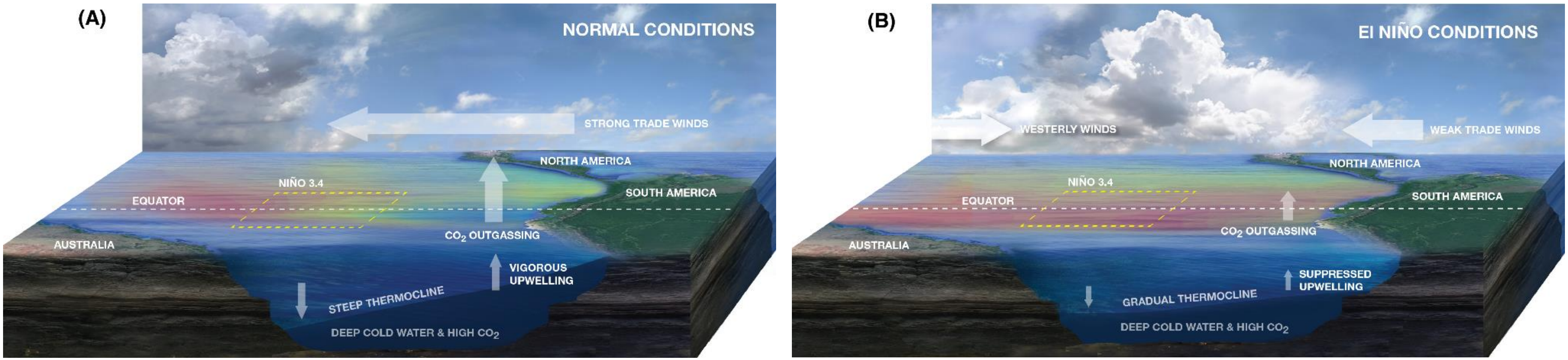
OCO-2 Observations of the 2015-2016 El Niño



How did the Carbon Cycle Respond to the 2015-2016 El Niño?

- OCO-2 was launched less than 9 months before the onset of the intense 2015-2016 El Niño
- During recent El Niños, the rate of CO_2 buildup has increased, but there are several unanswered questions:
  - What are the relative roles of the ocean and the atmosphere in the observed CO_2 increases?
  - What are the relative roles of drought, heat stress, and fire on the emissions of CO_2 from land during El Niño?
  - What are the implications of these changes for Climate/Carbon Cycle interactions as the climate warms?
- The unprecedented resolution and coverage provided by OCO-2 provides new ways to address these other questions about interactions between the climate and carbon cycle

Carbon system in the Tropical Pacific

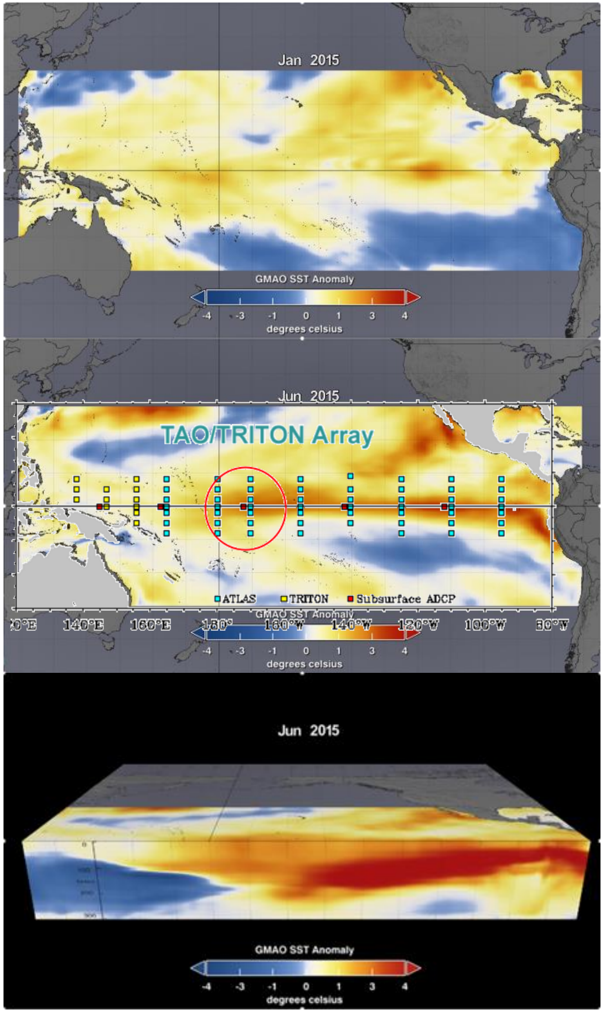


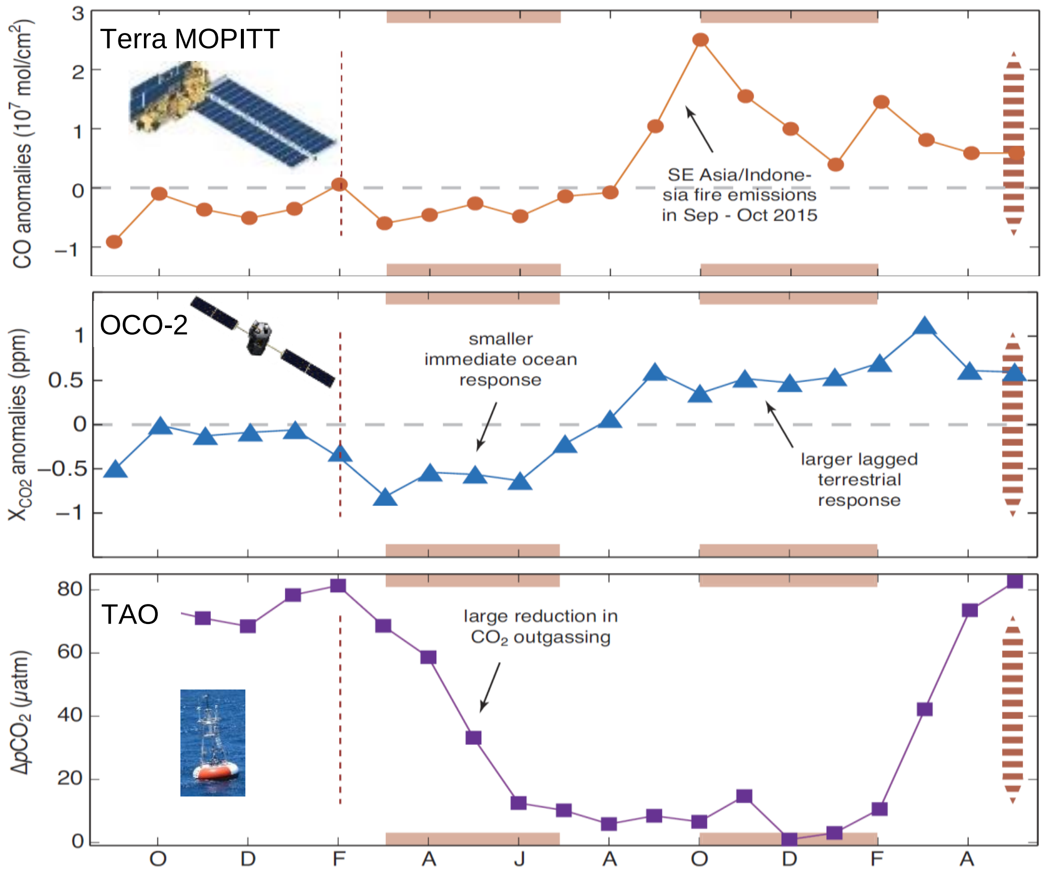
Dijkstra [2006]

- **Normal conditions: upwelling of cold subsurface waters that have high potential pCO_2 + inefficient biological pump → strong CO_2 outgassing**

- **El Niño conditions: deepening of thermocline, reduction in upwelling, weakening of trade winds + more efficient biological pump → decreases CO_2 outgassing by 40-60%**

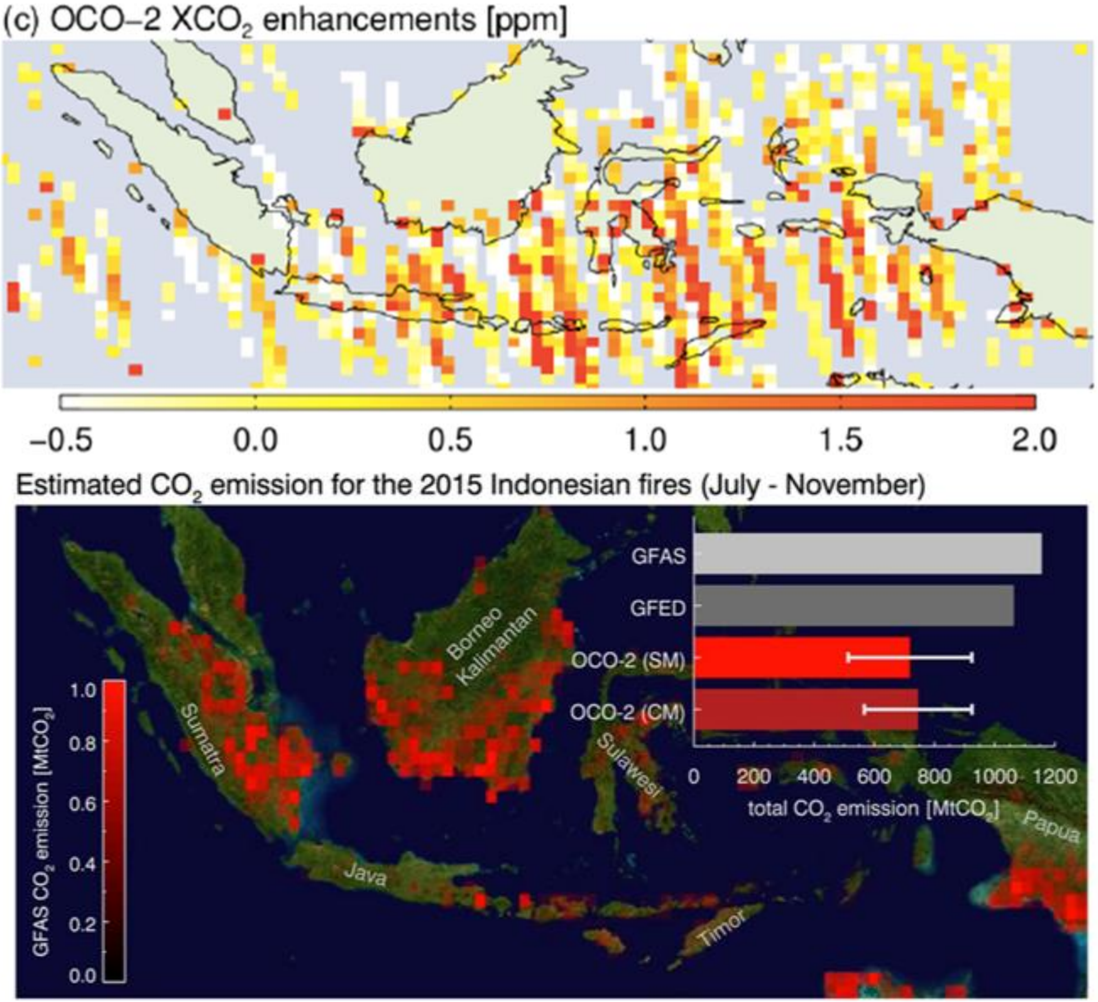
2015-2016 El Niño: Ocean Response





Abhishek Chatterjee et al. (2017)

2015-2016 El Niño: Fires

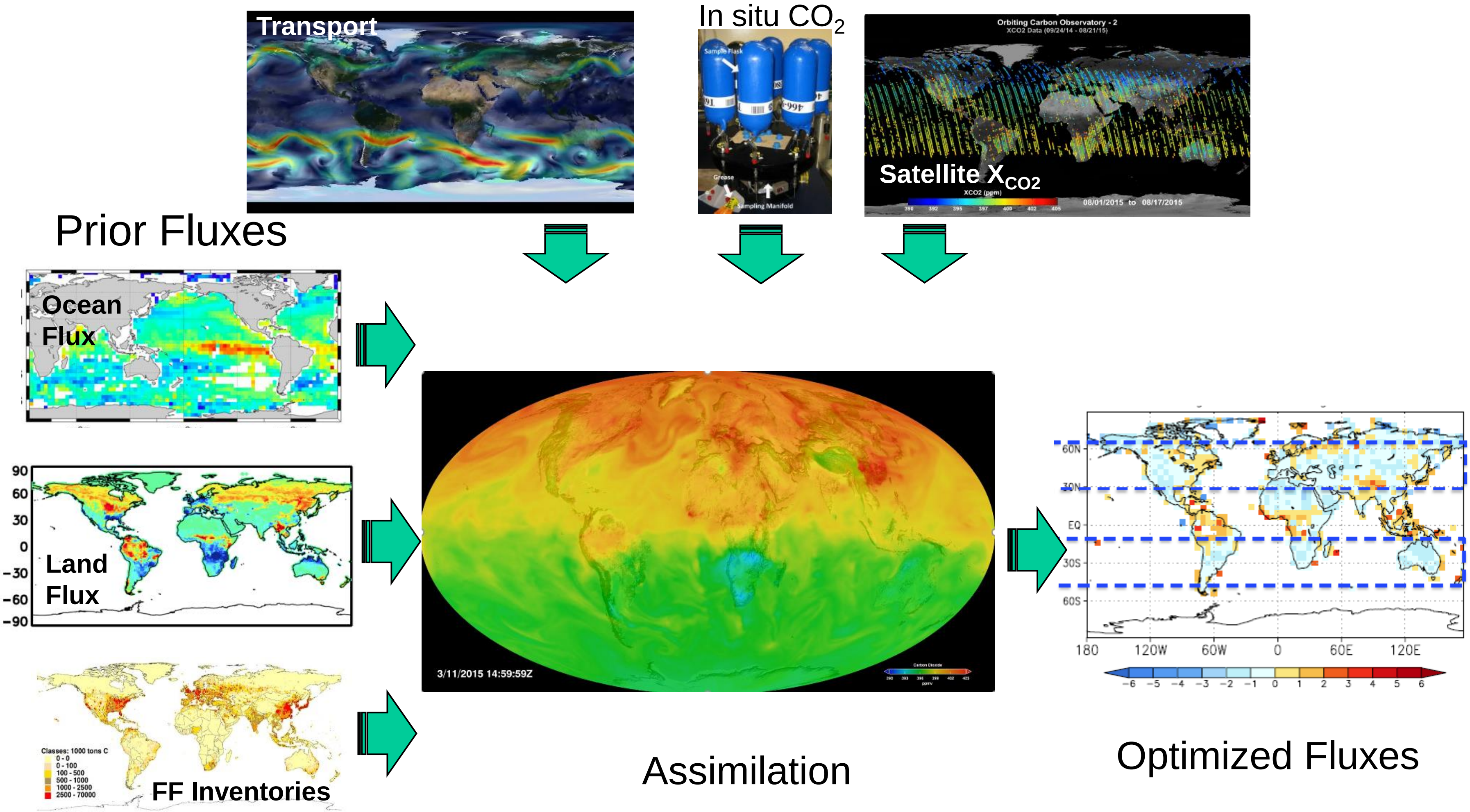


Jenns Heymann et al. (GRL, 2017)

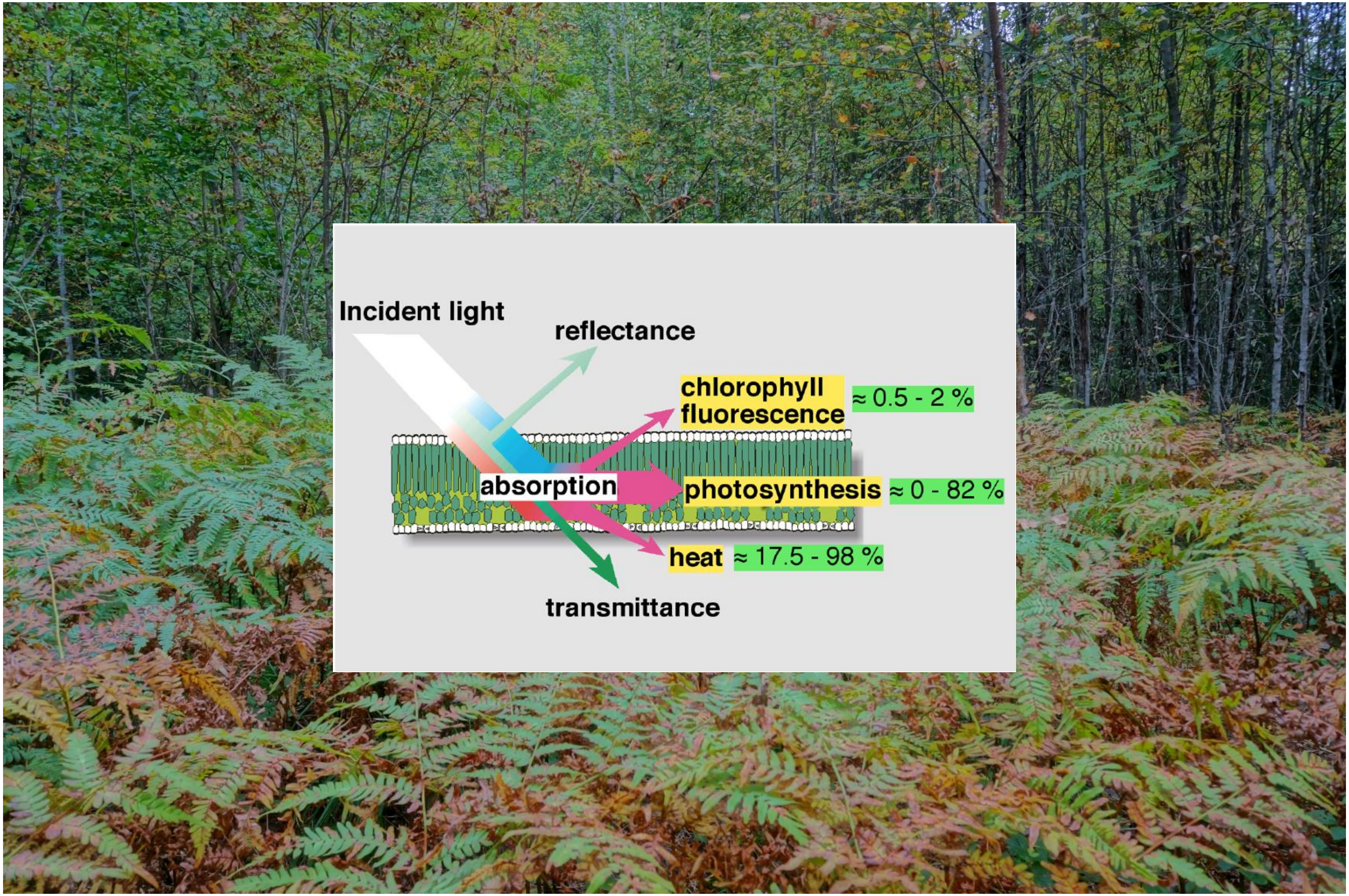
X_{CO2} enhancements over Indonesia observed by OCO-2 between July and November 2015.

Fire emissions estimates from the GFAS and GFED inventories to emission estimates obtained from OCO-2 data, using two analysis approaches. The OCO-2 estimates are less than 70% as large as those in the inventories.

“Top-Down” Flux Inversion Estimates



Solar-Induced Chlorophyll Fluorescence (SIF)



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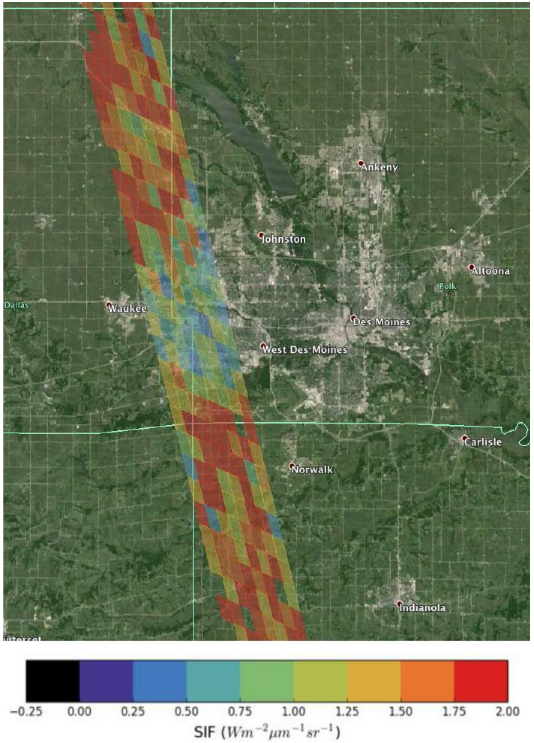
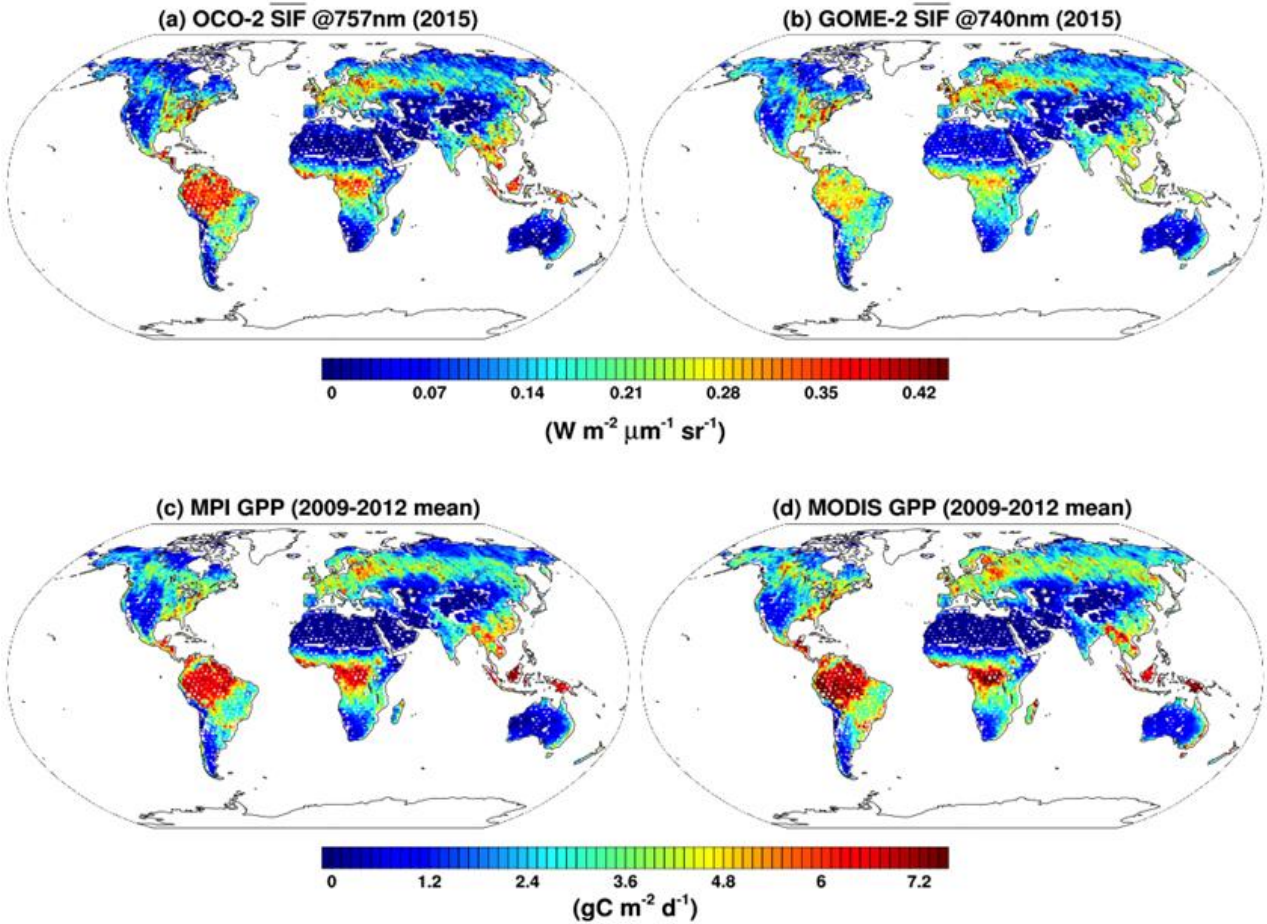


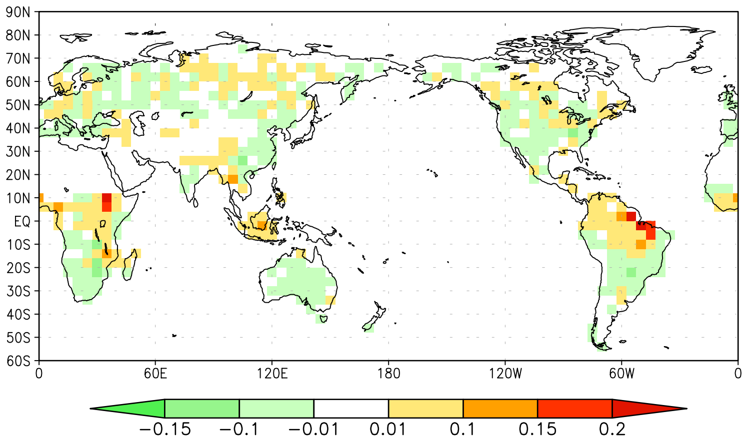
OCO-2 SIF over Des Moines, Idaho



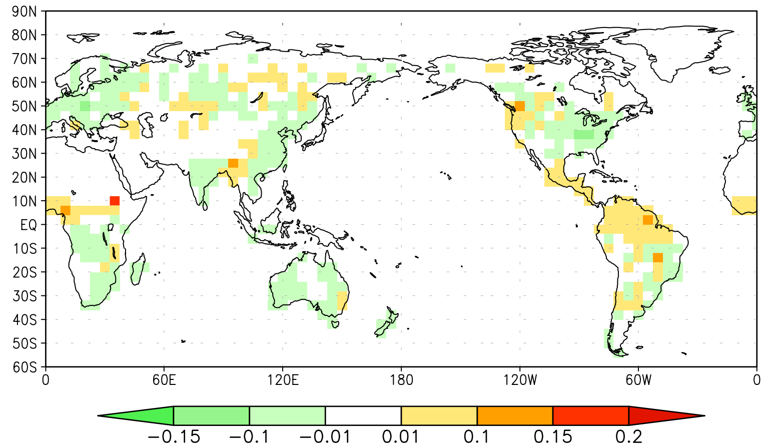
Ying Sun et al. (2017)

2015 El Niño and 2011 La Niña annual biosphere fluxes and their differences

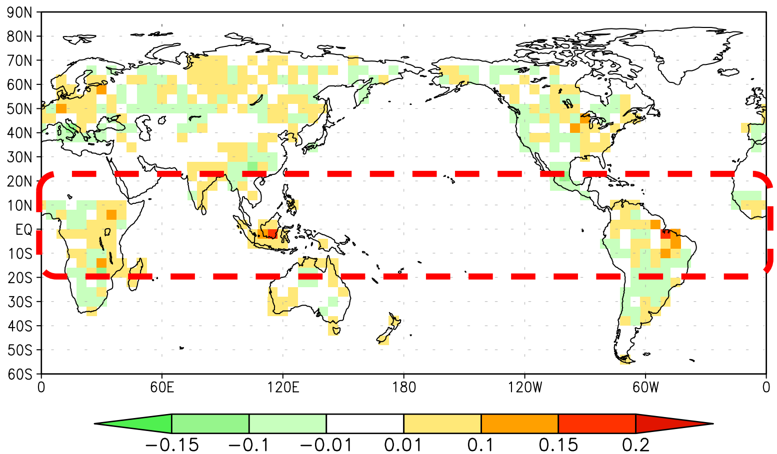
2015 (GtC/yr)



2011 (GtC/yr)



2015- 2011 (GtC/yr)



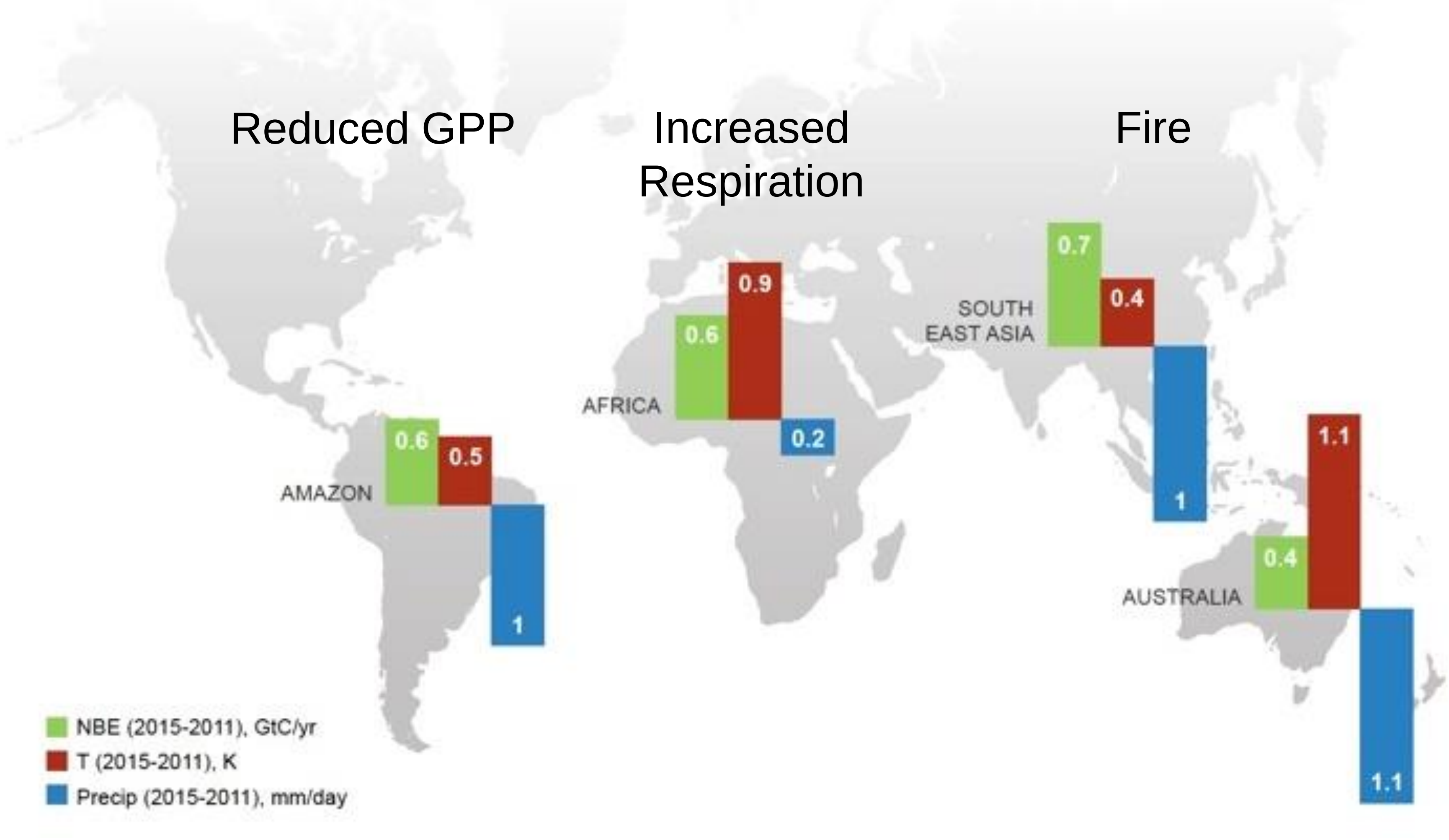
Red: release CO_2 into atmosphere

Green: absorb CO_2 from atmosphere

- **The most significant impact of 2015 El Niño on biosphere carbon fluxes is the increase of CO_2 release from the tropics**

Junjie Liu et al. (2017)

2015-2016 El Niño: 3 Continents, 3 Stories



Key Results

- OCO-2, with its unprecedented coverage over the tropical Pacific Ocean, provides a first-hand look at the space-time evolution of atmospheric CO2 concentrations during the 2015-2016 El Niño
- Oceans do contribute to the ENSO CO_2 effect
  - Suppressed outgassing from the oceans happen early, followed by a larger (and lagged) response from the terrestrial component
  - The net increase in atmospheric CO_2 would be even larger in the absence of this ocean outgassing
- The topical land biosphere response can vary from continent to continent, due to the competing effects of drought, heat stress and fire, all of which reduce CO_2 uptake
  - These processes may play increasingly important roles as the tropical climate evolves

Summary

- **Space-based remote sensing observations hold substantial promise for future long-term monitoring of greenhouse gases**
  - **These data complement existing ground-based and aircraft based in situ data with increased coverage and sampling density**
- **The GOSAT and OCO-2 missions are beginning to demonstrate these capabilities**
  - **GOSAT and OCO-2 teams have pioneered methods for cross-calibrating measurements and cross-validating products**
  - **Their products have been combined to produce an 8-year record that is now being used in studies of the global carbon cycle**
- **A new OCO-2 data product (B8) has been delivered to the Goddard Earth Science Data and Information Services Center (GES-DISC) for distribution to the science community:**

https://disc.gsfc.nasa.gov/datasets?page=1&source=OCO-2%20OCO%20SPECTROMETERS